A Final Report
on

EFFECTS OF SOIL AND CANOPY CHARACTERISTICS ON MICROWAVE BACKSCATTERING OF VEGETATION

Prepared by

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ABSTRACT

A frequency modulated continuous wave C-band (4.8 GHz) scatterometer was mounted on an aerial lift truck and backscatter coefficients of corn (Zea mays L.) were acquired as functions of polarizations, view angles, and row directions. As phytomass and green leaf area index increased, the backscatter also increased. Near anthesis when the canopies were fully developed, the major scattering elements were located in the upper 1 m of the 2.8 m tall canopy and little backscatter was measured below that level. C-band backscatter data could provide information to monitor tillage operations at small view zenith angles and also to monitor vegetation at large view zenith angles.

C-band backscattering from corn canopies

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Abstract. A frequency-modulated continuous-wave C-band (4·8 GHz) scatterometer was mounted on an aerial lift truck and backscatter coefficients of corn (*Zea mays* L.) were acquired as functions of polarizations, view angles and row directions. As phytomass and green-leaf area index increased, the backscatter also increased. Near anthesis, when the canopies were fully developed, the major scattering elements were located in the upper 1 m of the 2·8 m tall canopy and little backscatter was measured below that level for view angles of 30° or greater. C-band backscatter data could provide information to monitor tillage operations at small view zenith angles and vegetation at large view zenith angles.

1. Introduction

For more than two decades, scientists have studied separately the properties of vegetation in the optical and microwave regions of the electromagnetic spectrum. Each spectral region appears to contain unique information about vegetation. Measurements by optical sensors depend on the differential scattering and absorption caused by chlorophyll, leaf structure, green-leaf area, leaf water content and soil background (Bunnik 1978, Kollenkark *et al.* 1982). Microwave sensors respond to larger-scale structure of the canopy, plant water content, plant-part size distributions and soil surface conditions (Attema and Ulaby 1978, Brunfeldt and Ulaby 1984 a, Dobson *et al.* 1984, Ulaby *et al.* 1978). Until recently, most microwave research related to vegetation focused only on species identification or the effects of vegetation on the determination of soil moisture. Strong evidence suggests that the backscatter returns of active microwave systems are related to vegetation density and canopy structure (Brunfeldt and Ulaby 1984 a, Sieber 1985). Thus microwave remote sensing offers the potential to differentiate more effectively among certain cover types than may be possible with optical data.

The parameters affecting optical and microwave radiation appear to be complementary in that they represent different, but interrelated, aspects of the scene. Because the physical parameters affecting both optical and microwave radiation are related to the quantity and quality of phytomass, the opportunity exists to utilize remote

sensors to obtain data that are needed to model the growth and net productivity of vegetation. These are key concerns for modelling global carbon cycles, as well as assessing the ability of ecosystems to support human life.

Microwave remote sensing offers the potential to obtain information on vegetation and soils independently of most weather conditions. Schmugge (1983) summarized the capability of microwave systems to estimate soil moisture and emphasized that the backscatter response is a function of view angle, soil surface roughness, and the dielectric properties of the soil and the vegetation.

The scattering behaviour of the canopy is governed by the dielectric properties and geometric configurations of the scattering elements (i.e. leaves, stems and fruit). Because the dielectric constant of water is much greater than the dielectric constant of dry vegetation, water content plays a dominant role in determining the backscatter from a canopy. Attema and Ulaby (1978) developed a first-order canopy backscattering model by treating the canopy as a cloud containing many droplets of water suspended in the volume occupied by the vegetation and assuming that the vegetation had a uniform scattering phase function. The backscatter coefficient in their model integrated the contributions of the number of water droplets per unit volume over the path length of the signal through the canopy. Thus the backscattering coefficient of the target in their cloud model is a function of the volumetric moisture content of soil, the volumetric water content of the vegetation, and plant height.

Ulaby *et al.* (1984) improved the applicability of the cloud model by providing for backscatter contributions from leaves, stalks and soil. The multicomponent cloud model for corn and sorghum has two layers: an upper layer dominated by leaves and a lower layer dominated by stalks. Backscatter from the soil in the multicomponent model is attenuated by both layers of vegetation. More recently Ulaby *et al.* (1987) developed and tested with field data a new model that accounts for both scattering and intrinsic absorption by stalks (treated as cylinders) and leaves (treated as small randomly oriented discs). The model agreed well with experimental data at 1·6 and 4·8 GHz but underestimated extinction at 10·2 GHz. They concluded that their models of loss due to vegetation presence were best suited when leaves were smaller than the wavelength.

Little microwave research has attempted to assess the vigour and productivity of vegetation, characteristics frequently used in models of ecosystems. Ulaby *et al.* (1984) recognized this void and developed empirical models in terms of a single biophysical characteristic of vegetation, i.e. leaf-area index (LAI), which is the area of one side of leaves per unit area of soil. In their model the backscatter coefficient measured at an angle of 50° and a frequency of 13 GHz appeared to approach an asymptote as LAI exceeded approximately 3·0 for corn and sorghum, but not for wheat. No explanation was offered for the differences in backscatter response among the crops. Possibly the differences in backscatter are related to the sizes of the foliage elements compared with the wavelength of the radar. At 13 GHz the wavelength is 23 mm. Leaves of corn and sorghum are several wavelengths wide, while leaves and stems of wheat have cross-sections less than one wavelength.

A key research issue is how to determine important characteristics of vegetation using multispectral (optical and microwave) remote sensing. Additional research is required to determine the backscatter response for the wide ranges of LAI and phytomass expected in cultivated and natural vegetation. The objective of this research is to determine relationships between C-band (4·8 GHz) backscatter and agronomic characteristics of corn (*Zea mays* L.) canopies.

2. Approach

2.1. *Experiment design*

Several experiments were conducted at the Purdue University Agronomy Farm from 1984 to 1986 on a Chalmers silt loam soil (typic Argiaquol). In 1984 four densities (2·5, 5, 10 and 15 plants/m^2) of corn (*Zea mays* L. 'Pioneer 3732') were planted in 0·76 m rows on 14 May and 4 June 1984. In 1985 corn ('Becks 65X') was planted on 23 May at three densities (2·5, 5 and 10 plants/m^2) in 0·76 m wide rows and three densities (5, 10 and 20 plants/m^2) in 0·38 m wide rows. In 1986 one density (9·2 plants/m^2) or corn ('Becks 65X') was planted in both 0·38 and 0·76 m wide rows. Ridges† 0·2–0·3 m high were formed in one half of the plots with 0·76 m wide rows in 1986 by cultivation 42 days after planting, when the corn was 0·7 m high. Additional plots of bare soil with and without ridges were also established. All plots were at least 18 m by 30 m. High levels of soil fertility were maintained by applying 250, 44 and 130 kg/ha of N, P and K respectively, as indicated by soil tests. Weeds were controlled with herbicides and by hand weeding when necessary.

2.2. *Data aquisition*

A frequency-modulated–continuous-wave (FM–CW) C-band scatterometer with a centre frequency of 4·8 GHz was built by the Remote Sensing Laboratory at the University of Kansas (Brunfeldt and Ulaby 1984 b). The scatterometer has a 3·6° conical beam annd transmits a continuous beam of coherent microwaves with either vertical (V) or horizontal (H) polarization. The system also receives either V or H polarization. Thus four transmitted and received polarizations are possible: HH, VV, HV and VH (the first letter indicates the transmitted polarization and the second the received polarization). In these experiments we measured both like-polarizations (HH and VV) but only one cross-polarization (HV). The scatterometer and a 35 mm camera were mounted on an aerial lift truck and elevated 12 m above the soil. As the truck moved slowly along the edge of a plot, 30 independent samples of backscatter were recorded for a selected polarization and view-angle combination. The backscatter coefficient is the ratio of the power received per unit area divided by the power transmitted and the area irradiated. The portion of the power received owing to thermal noise and feedback was measured by pointing the scatterometer skyward and recording backscatter as a function of range for each polarization (Paris 1986). The mean noise of the system decreased from less than −40 dm at 10 m to less than −60 dB at 30 m. A regression of the noise as a function of range was used to correct backscatter coefficients of the targets; however, this correction was very small relative to the backscatter received from the targets. Periodically the scatterometer was calibrated using an active radar calibrator (Brunfeldt and Ulaby 1984 c).

Two series of experiments were conducted with the C-band scatterometer. In the first series the range resolution was 13·5 per cent of the distance between the antenna and the target, and backscatter was recorded as a function of view zenith angle (0°, 10°, 20°, 30°, 40°, 50° and 60°), polarization, and view azimuth relative to row direction (i.e. parallel or perpendicular to row direction). These measurements were repeated at various stages of development of the corn. Because the transmitter and

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† Ridge cultivation is a conservation tillage practice in which broad ridges 0·2–0·3 m high are formed by cultivation that brings soil from the middle of the rows against the plants on both sides. Subsequent crops are planted on top of the ridges with a minimum of tillage prior to planting.

receiver are coaxially aligned and uses the same antenna, illumination and view angles are equal and will be referred to as view angle in this paper.

For the second series of experiments the range resolution of the scatterometer was changed to 4 per cent of the range by widening the modulation bandwidth from 400 to 650 MHz and adding two additional 3 dB attenuators to improve noise performance. This modification permitted more precise determination of the location of the major scattering elements within a canopy. In this series of experiments backscatter was recorded as the range was systematically adjusted to move the sensed volume from above the canopy, into the canopy and to the soil surface. Thirty independent samples of backscatter were aquired as a function of range, view zenith angle (10°, 30° and 50°), polarization and relative view azimuth direction.

Five plants from each plot were selected at random, cut at the soil surface, weighed individually (total fresh phytomass), separated into green leaves, brown leaves, stems and ears, weighed (fresh pphytomass of components), dried to constant weight at 70°C, and weighed (dry phytomass of components). The area of all green leaves was measured with an optical planimeter (LI-COR LI-3100†), and the leaf-area index (LAI), the area of one side of leaves per unit area of soil, was calculated for each plant density. In the second series of experiments phytomass and leaf area were also determined in 0·5 m layers starting at the soil surface.

The volumetric moisture content of the top 6 cm of soil was dettermined for five locations per plot on each date. Soil surface roughness was measured at 10 locations parallel and perpendicular to the rows in each plot using a 1·0 m long microrelief meter (Burwell *et al.* 1963) with 3·2 mm ($\frac{1}{8}$ in. diameter pins spaced 10 mm apart.

3. Results and discussion

3.1. *View angle*

Backscatter coefficients for HH polarization decreased rapidly as view zenith angle increased from 0° (vertical) to approximately 20° (figure 1). Changes in backscatter were much smaaller at view zenith angles greater than 30°. Although not shown, both VV backscatter responded similarly to changes in view angle. The shapes of the backscatter curves in 11 June (figure 1) are typical of relatively smooth bare soil (Ulaby *et al.* 1978). In June, when the plants were small (table 1), vegetation had little effect on backscatter from soil. In August, when the canopies were fully developed, the vegetation increased backscatter by more than 5 dB at view angles greater than 30°, but the differences in backscatter from 2·5 and 10 plants/m² are small. Thus assessing subtle, but important, changes in phytomass of corn may be difficult at C-band wavelengths.

The effects of view zenith angle on C-band backscatter are further demonstrated by the results shown in figures 2 and 3 for HH and HV polarizations respectively. Here the backscatter response from dense corn canopies growing over soils with smooth and rough surfaces are compared with measurements of bare soil with similar roughness characteristics and soil moisture contents (table 2). Figure 4 shows representative profiles of the smooth and rough (ridge) soil surfaces. The ridges averaged 0·22 m from top to bottom and presented a rough undulating surface with a periodicity of 0·76 m ((i.e. the row spacing) when viewed perpendicular to row direction (figure 4(c)). Even parallel to the row direction (figure 4(b)), the ridges are

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† Company and trade names are given for the benefit of the reader and do not imply any endorsement of the product or company by the U.S. Department of Agriculture.
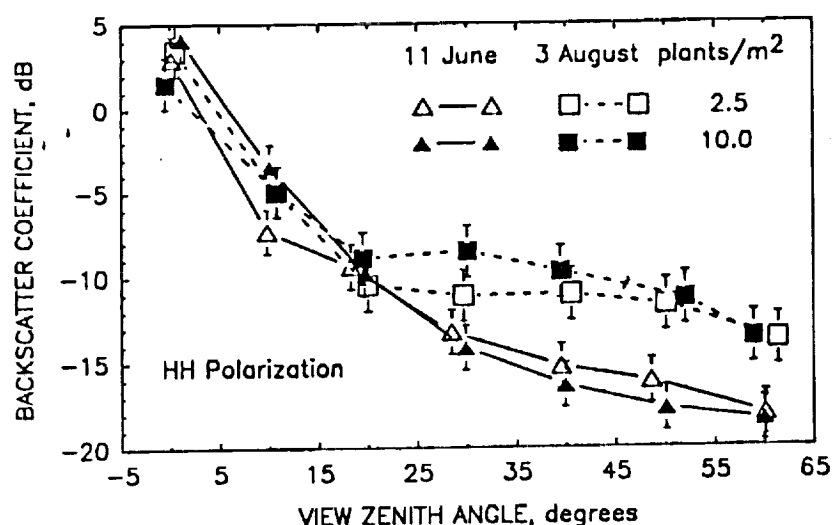
Figure 1. Changes in backscattering coefficients of two corn canopies on two dates as a function of view zenith angles with HH polarization. Each point represents 30 independent samples of the backscatter acquired at a view azimuth parallel to the row direction. Root mean square (r.m.s.) errors are 1·3 dB for 11 June and 1·5 dB for 3 August. Agronomic data describing these canopies are presented in table 1.

rougher than the smooth soil surface (figure 4(a)). Clods of soil created when the ridges were formed account for the roughness of the ridge sides.

The smooth bare soil surface exhibited the highest HH backscattering coefficient, for view zenith angles near vertical, but the HH backscatter decreased rapidly as view zenith angle increased to 20° (figure 2(c)). Smooth soil surfaces scatter more radiation in the forward or specular direction than rough surfaces. In most cases both HH and HV backscatter of corn was significantly higher than that for smooth bare soil for view zenith angles greater than 20°. (The r.m.s. errors for HH and HV are 1·4 and 1·1 dB, respectively, and are equal to or smaller than the symbols in figures 2 and 3.) Row direction had little or no significant effect on backscatter from the corn growing in the smooth soiil.

Table 1. Green-leaf-area index and total above ground phytomass of corn for two dates in 1984 corresponding to the backscatter coefficients presented in figure 1.

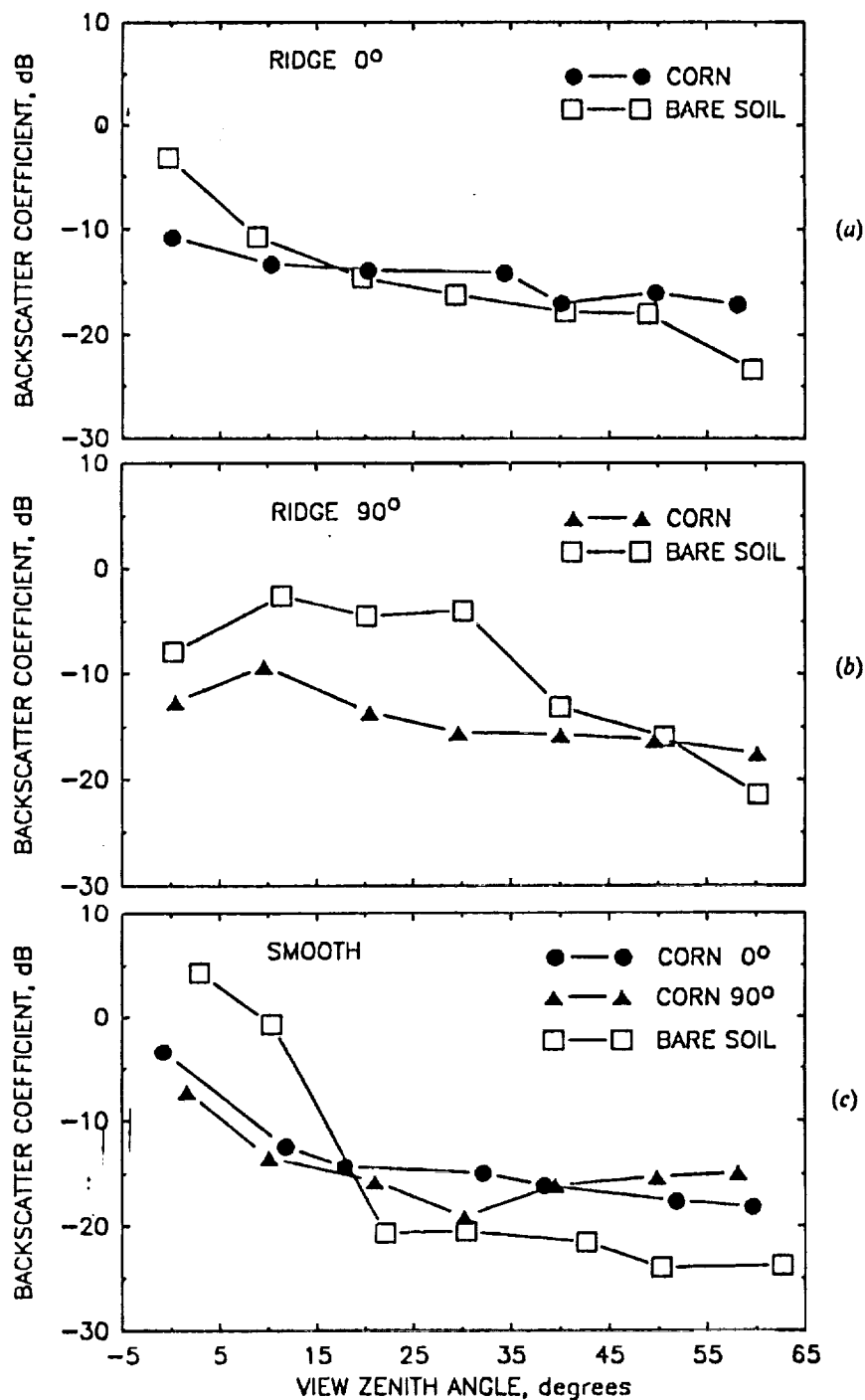| Plant density (plants/m²)	Height (m)	LAI	Total phytomass (kg/m²)		Soil moisture (per cent)
			Fresh	Dry	
11 June					
2·5	0·4	0·5	0·46	0·056	11·4
5·0	0·4	0·8	0·80	0·095	11·4
10·0	0·4	1·8	1·51	0·185	11·6
3 August					
2·5	2·4	1·3	3·64	0·706	12·4
5·0	2·4	2·2	5·14	1·014	12·5
10·0	2·5	3·7	6·57	1·281	12·7

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Figure 2. Effects of view zenith and azimuth angles on HH backscattering coefficients of corn and bare soil on 28 July 1986. Each point represents 30 independent samples of the backscattering coefficient acquired at view azimuths parallel (0˚) or perpendicular (90˚) to the row direction. The r.m.s. error is 1·4 dB and is approximately the size of the symbols used. Agronomic data describing these canopies are presented in table 2. The ridges were formed three weeks prior to these measurements.
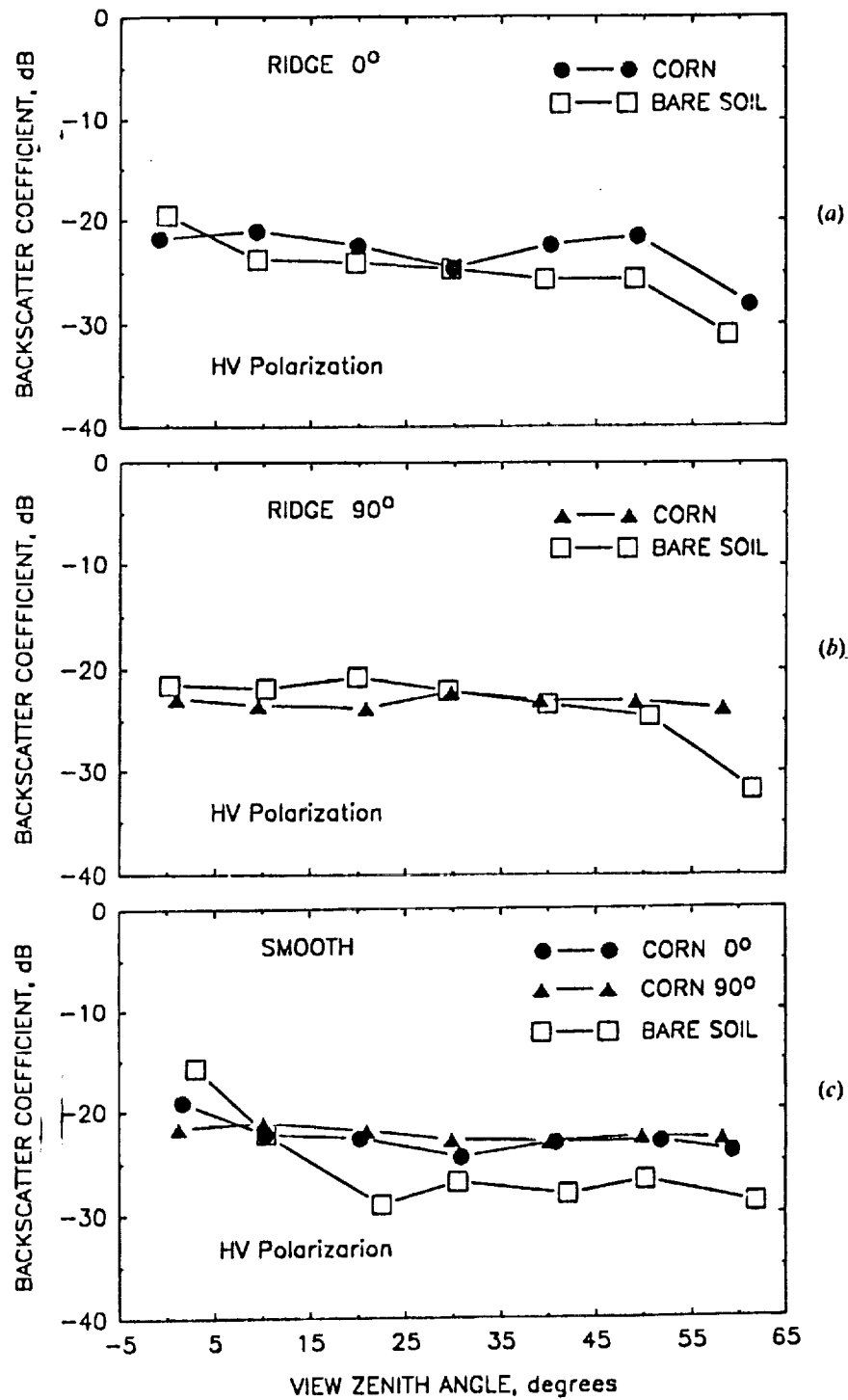
Figure 3.   As figure 2 but for HV polarization. The r.m.s. error is 1·1 dB.

Table 2.   Green-leaf-area index and total above ground phytomass for corn on 28 July 1986 corresponding to the backscatter coefficients presented in figure 2.

Tillage	Height (m)	LAI	Total phytomass (kg/m²)		Soil moisture (per cent)
			Fresh	Dry	
Smooth	2·8	4·8	6·08	1·044	8·7
Ridge	2·8	4·6	6·03	1·081	8·1

When the scatterometer was oriented parallel to the row direction (relative azimuth 0°) for the ridged soil plots (figure 2 (*a*)), the HH backscatter from bare soil was higher than the backscatter from vegetation at small view zenith angles (figure 2 (*a*)). However, in contrast with the smooth-soil case (figures 2 (*c*) and 3 (*c*)), both HH or HV backscatter from vegetation was consistently significantly different from the rough bare soil over the 10°–40° range of view zenith angles (figures 2 (*a*) and 3 (*a*)). At view angles greater than 50° the backscatter from the corn was significantly higher than from bare soil.

With the scatterometer oriented perpendicular to the ridges (relative azimuth 90°), the effect of the vegetation on HH backscattering is striking (figure 2 (*b*)). The HH
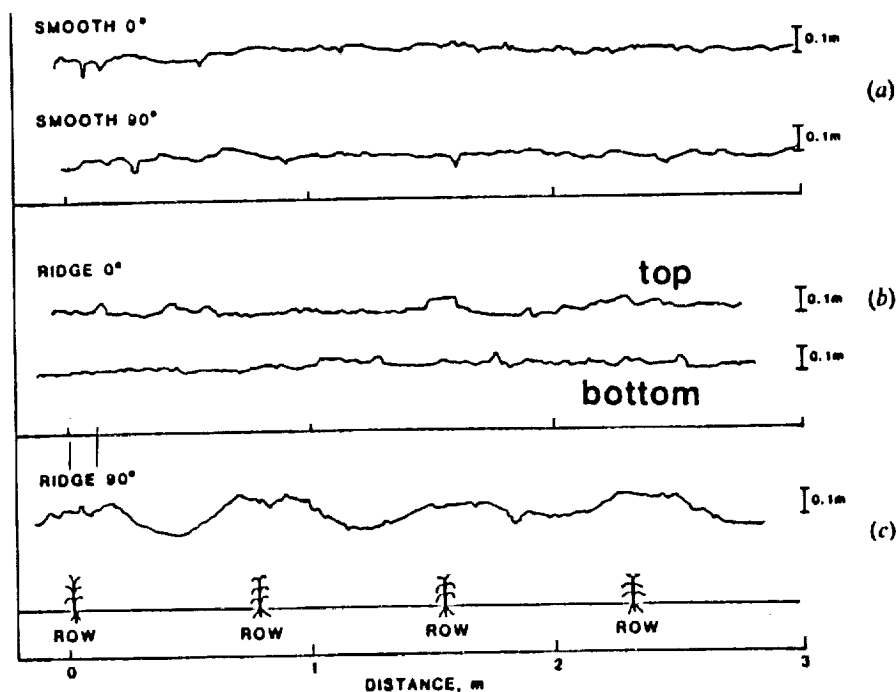

Figure 4.   Representative profiles of soil roughness in corn with smooth (*a*) and ridged ((*b*) and (*c*)) soil surface. In the ridged soil, the profiles are parallel (*b*) and perpendicular (*c*) to the ridges. Clods of soil created when the ridges were formed account for the roughness of the ridge sides. The vertical bars along the right-hand side represent 0·1 m change in the altitude of the surface. The rows are 0·76 m apart.

backscatter from the bare soil with ridges was higher than the smooth bare soil for the 0°–30° view angles because of a strong radar return from the ridge slopes. The mean slope of the ridges was 26° ± 6°, which presented a surface approximately perpendicular to the transmitted radar beam (figure 4(c)). The presence of the dense corn canopy significantly attenuated the HH backscatter from the soil ridges (figure 2(b)), but not the HV backscatter (figure 3(b)). For example, HH backscatter was 12 dB lower for the corn canopy than for the bare soil at a 30° view zenith angle. The presence of dense vegetation decreased measured HH backscatter from the rough undulating surfaces (figure 2(c)), but increased backscatter relative to smooth soil conditions (figure 2(c)). An analogous situation has been observed in the visible-wavelength region, where soils may be darker or brighter than vegetation and the scene reflectance may increase or decrease as vegetation cover increases (Bunnik 1978, Kollenkark *et al.* 1982).

3.2. *Backscatter as a function of range*

By systematically varying the range, the backscattering cross-section of the canopy as a function of range or depth into the canopy was measured (figure 5). For example, consider a plane wave incident on a homogeneous semi-infinite canopy. As the wave encounters the canopy, the backscattered power rises rapidly, but is attenuated
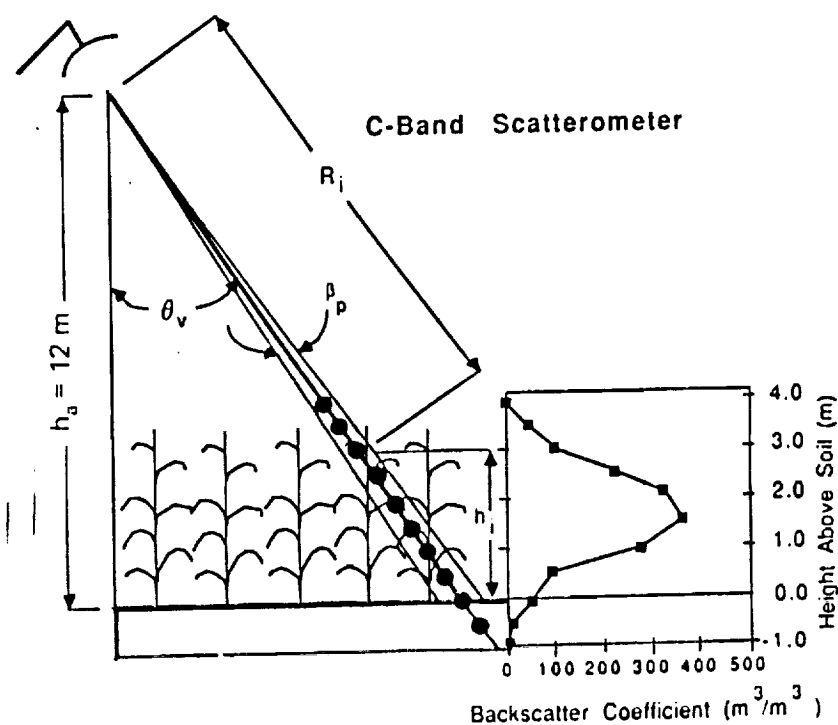

Figure 5. Schematic of C-band scatterometer with field of view β_p and view zenith angle θ_v measuring incremental backscatter as function of depth into the canopy. The scattering volume centers for range R_i and height above soil h_i are shown as large dots along the viewing direction. The plot on the right presents typical data from this measurement setup.
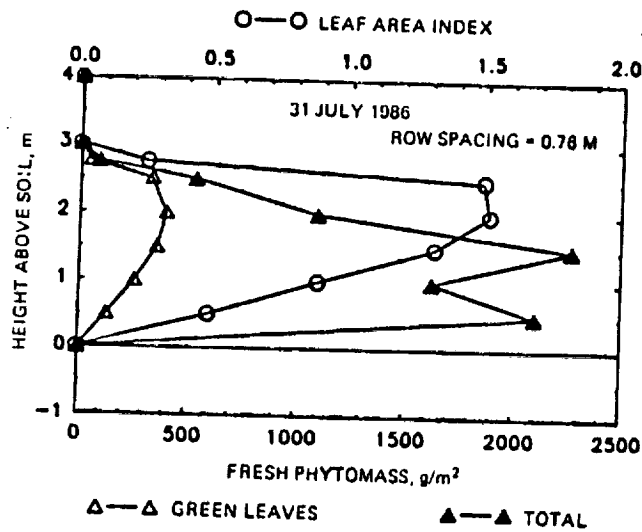
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(a)

(b)

(c)

BACKSCATTER COEFFICIENT, m³/m³

O——O LEAF AREA INDEX
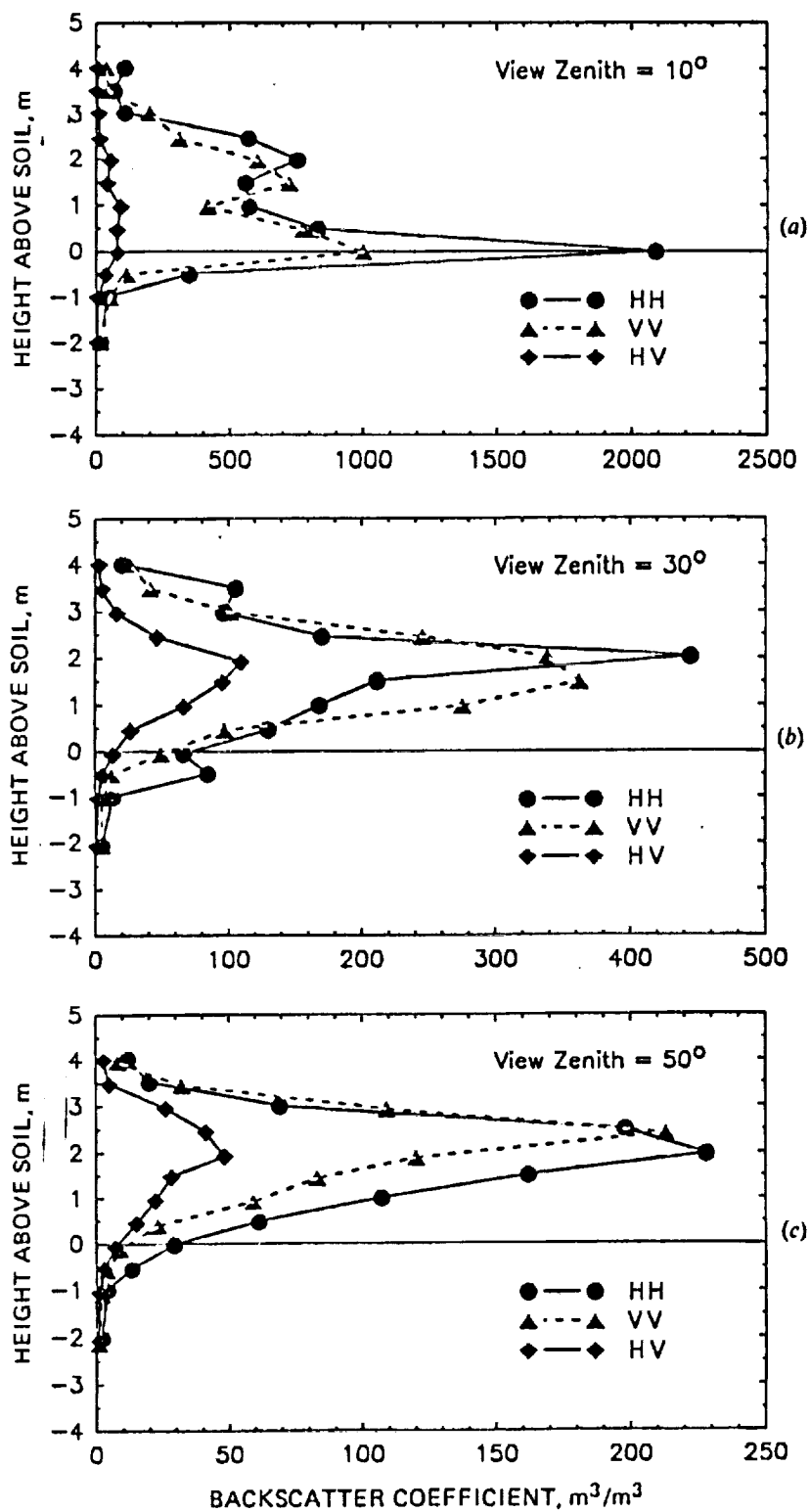
Figure 7. Phytomass and leaf area of corn in 0·5 m layers above the soil. Data are for corn in 0·76 m wide rows. The sum for all layers are LAI = 5·9, green leaves 366 g/m² and total dry phytomass 1537 g/m².

exponentially as it penetrates deeper into the canopy. To obtain the canopy backscattering coefficient, one must integrate the incremental backscattering coefficient through the total canopy range (Paris 1986, Wu 1986). Pitts *et al.* (1986) calculated scattering and extinction coefficients using the incremental C-band backscattering data for tree canopies. Figure 5 illustrates how the range of the scatterometer was systematically adjusted to move the sensed volume from above the canopy into the canopy. The scatterometer range setting for determining the height of the sensed volume above the soil may be calculated using the following equation:

$$R_i = \frac{h_a - h_i}{\cos \theta_v}$$

where R_i is the distance from the antenna to the sensed volume, h_a is the antenna height above the soil, h_i is the height of the sensed volume above the soil and θ_v is the view zenith angle of the scatterometer. Backscatter was measured as a function of height above the soil in 0·5 m increments.

The changes in the incremental backscattering coefficient of corn planted in 0·76 m wide rows are shown in figure 6 for three polarizations and three view zenith angles. Similar changes were observed, but are not shown, for corn in 0·38 m wide rows. The corresponding agronomic data for 0·5 m layers are shown in figure 7. Negative heights indicate that the slant range from the antenna to the target was greater than the actual distance to the soil surface, and the measured backscatter may have come from multiple scattering within the canopy.

Figure 6. Changes in the backscattering coefficient for corn planted in 0·76 m rows as a function of depth into the canopy. Each point represents 30 independent samples of backscatter acquired at view zenith angles of 10°, 30° and 50° and at a view direction parallel to the row direction. The soil surface was smooth.

At a view zenith angle of 10° the majority of the returned signal originated at the soil surface, with very little backscattering from the vegetation (figure 6(a)). This confirms the observations by Ulaby *et al.* (1978), as well as our results illustrated in figure 2, indicating that soil roughness influences C-band backscatter at small view angles even in the presence of vegetation. At view zenith angles of 30° and 50° the maximum backscattering was measured at 2·0 m above the soil (figures 6(b) and (c)), which corresponded to the volume of the canopy with the largest leaf area (figure 7). The greatest total phytomass was measured in the layer at 1·5 m above the soil, which corresponded to the layer with the developing ear and grain. Very little of the backscattered signal originated at the soil surface for the 30° and 50° view angles. Thus, when the canopies were fully developed, the majority of the scattering elements were located in the upper 1·0 m of the 2·8 m tall corn. Polarization had little effect on penetration into these dense corn canopies, i.e. on the height at which the maximum backscatter was observed. The height of the maximum cross-polarization (HV) backscatter corresponded to the height of the maximum backscatter for the like-polarizations. View direction relative to row direction did not significantly alter the pattern of penetration of the microwaves.

4. Summary and conclusions

Backscatter coefficients of corn canopies were measured as functions of view angle, polarization, and view directions relative to row direction. At view angles of 20° or less soil conditions dominated the backscatter coefficients, with smooth soil surfaces increasing backscatter. At view angles greater than 20° the influence of vegetation on the backscatter increased, and rough soil surfaces increased backscatter particularly when row direction was perpendicular to the view direction. For fully developed corn canopies the majority of the backscattered signal comes from the upper 1·0 m of the canopy, with little radiation reaching and being backscattered from the soil.

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